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Professor Richard Serfozo

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sch of Industrial & Sys Eng
Georgia Institute of Tech
Atlanta, GA 30332

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The general theme of the research has been to develop stochastic network processes for modeling the movement of discrete units in networks. Primary examples are the movement of parts and supplies in manufacturing plants and in distribution systems and the movement of data packets and telephone calls in computer and telecommunications networks. The distinguishing feature of the research is the emphasis on the next generation of intelligent networks that will be the backbone of the manufacturing and computer systems. In these networks, the processing of units at the nodes and the routing of units typically depend dynamically on the actual network congestion, and units move concurrently (e.g. batch processing) most of the present theory of stochastic network processes is for unintelligent networks in which the nodes operate independently, the routes of units are independent, and the units move one-at-a-time. The goal is to provide an understanding of these more complex intelligent networks by describing their stochastic behavior.

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February 27, 1994

Principal Investigator: Richard F. Serfozo, Professor

School of Industrial and Systems Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0205

(404) 894-2305

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The general theme of our research has been to develop stochastic network processes for modeling the movement of discrete units in networks. Primary examples are the movement of parts and supplies in manufacturing plants and in distribution systems and the movement of data packets and telephone calls in computer and telecommunications networks. The distinguishing feature of our research is the emphasis on the next generation of *intelligent* networks that will be the backbone of our manufacturing and computer systems. In these networks, the processing of units at the nodes and the routing of units typically depend dynamically on the actual network congestion, and units move concurrently (e.g. batch processing). Most of the present theory of stochastic network processes is for unintelligent networks in which the nodes operate independently, the routes of units are independent, and the units move one-at-a-time. Our goal is to provide an understanding of these more complex intelligent networks by describing their stochastic behavior. The following is a summary of the papers we have written for this project during the last year.

1 Relating the Waiting Times and Queue lengths in Heavy Traffic Systems by W. Szczotka, W. Topolski and the PI. To appear in *Stochastic Processes Appl.* 1994.

For a single-server queueing system, intuition suggests that an arriving unit's waiting time before its service begins is approximately equal to the number of units in the system times the average service time. Why are there no results to this effect? Because it is not true when the traffic intensity is moderate. However, we show that this approximation is indeed valid for certain systems in heavy traffic. We also give more insight into diffusion approximations for queueing systems. Namely, there are three types of natural diffusion approximations, not just the conventional reflected Brownian motion model. The results apply to rather general non-standard queueing systems in which the services may be highly dependent on the arrivals. We are currently writing another paper with a similar theme, involving more intricate analysis, for tree-like stochastic networks.

2 Extreme Queues and Stationarity of Service Systems in Heavy Traffic by Kuo-Hwa Chang. PhD dissertation in Industrial and Systems Engineering, Georgia Tech, 1993.

Knowledge of extreme queue lengths in service systems is needed for designing adequate space in manufacturing or communication systems or predicting when capacity constraints are violated. We show that the distribution of the maximum queue length in a time interval for a queueing system in heavy traffic converges to a new type of extreme value distribution. We also study the processes that record the number of times that the queue length exceeds a high level and the cumulative time the queue is above the level. We show that these processes converge in distribution to compound Poisson processes. The limiting extreme value distribution and compound Poisson processes we obtained can be used in practical computations similarly to the use of limiting normal distributions in central limit phenomena. We are currently writing two papers based on the results in this dissertation.

3 Little Laws for Waiting Times and Utility Processes by the PI. Submitted for publication, 1993.

Little's law for queueing systems is $L = \lambda W$: the average queue length equals the average arrival rate times the average waiting time in the system. Although there is considerable knowledge about this law, its applicability for many systems is still an open question. This study gives further insights into techniques for establishing such laws for new systems, and it presents several basic laws for systems with special structures. The main results concern (1) general necessary and sufficient conditions for Little laws for utility processes as well as queueing systems, (2) Little laws for systems that empty out periodically or, more generally, have regular departures (3) Little laws tailored to regenerative, Markovian and stationary systems and Little laws for stochastic networks. The motivation for a revisit to this subject was that the existing theory did not apply directly to stochastic network processes and further work was needed to obtain Little laws for networks.

4 Performance Analysis and Improvement of Parallel Simulation by Liang Chen. PhD dissertation in Industrial and Systems Engineering, Georgia Tech, 1993.

This covers the following topics:
(1) Comparison of several conservative parallel-simulation protocols with the Time Warp protocol.
(2) A Markovian model for analyzing the effect of memory capacity on Time Warp performance.
(3) Time Warp analysis for queueing network simulations.
(4) Space-Time Division protocols for feedforward parallel-simulations.

5 The Effect of Memory Capacity on Time Warp Performance by Akylidiz, I.F. Chen, L., Das, S.R., Fujimoto, R.M. and the PI. J. Parallel and Distributed Computing, 18, 411-422.

This is a study of a parallel simulation in which several interacting processes are synchronized by the *Time Warp* propocal and a "cancelback" scheme is used to reclaim storage when the system runs out of memory. A Markov process model is developed for describing the behavior of the simulation. Namely, it shows how the speedup of the system changes as the amount of memory is varied. The model is validated through performance measurements on a Time Warp system executing on a shared-memory multiprocessor using a workload similar to that in the model. It is observed that if the sequential simulation requires m message buffers, Time Warp with a small fraction of message buffers beyond m performs almost as well as Time Warp with unlimited memory.

6 Bounds on Speeds of Parallel Simulations That Satisfy a Conservation Principle by Chen L. and the PI. Submitted for publication, 1993.

Many parallel simulations have natural constraints on the number of processors that may usefully be employed. We provide insight into this constraint impasse by deriving upper bounds on the simulation speed (the rate at which it processes real events) for three processor-assignment schemes: fixed, global and local processor assignments. Our analysis is based on representing a parallel simulation as a random time transformation of the system being simulated. Using a sample path approach for stochastic processes, we show that a broad class of parallel simulations satisfy a conservation principle: The long run average virtual times in the simulation are equal (otherwise the virtual times will diverge from each other). We use this principle to derive the bounds and compare the efficiencies of the strategies.

7 Parallel Simulation by Multi-Instruction, Longest-path Algorithms by Chen, L. and the PI. Submitted for publication, 1993.

This paper presents several basic algorithms for the parallel simulation of G/G/1 queueing systems and certain networks of such systems. The coverage includes systems subject to manufacturing or communication blocking, or to loss of customers due to capacity constraints. The key idea is that the customer departure times are represented by longest-path distances in directed graphs instead of by the usual recursive equations. This representation leads to algorithms with a high degree of parallelism that can be implemented on parallel computers with single or multiple instruction streams.

8 Completion Times of Parallel Task Graphs: Extreme Values of Phase-type and Mixed Random Variables by Sungyeol Kang and the PI. A paper in preparation.

In manufacturing systems, a typical concern is the time it takes for a group of units that will eventually constitute one system to be processed by a network of work stations. This time is the maximum (or extreme value) of the travel times of the units through the network. An example is that 20 units must pass through a PERT network (or a task graph) before they are brought together as one system. The individual network completion times often have distributions that are of phase type or are mixtures of such distributions. This paper is a study of extreme values of such distributions. We show that the extreme value distribution of a large sample is asymptotically a Gumbel distribution. We apply these results to model completion times in a Markov task graphs and for group travel times in related networks.